Electromagnetic Design Techniques Enabling Control of the RFID Supply Chain

Phase I Final Report
Topic N04-179
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for the

Naval Facilities Engineering Center
Amphibious and Expeditionary Systems

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1. Purpose of Report

This report summarizes progress in the SBIR Phase I project "Electromagnetic Design Techniques Enabling Control of the RFID Supply Chain". During this project Wavelet Technologies, Inc. (WTI) has extended its genetic optimization program to include a variety of additional antenna geometries, worked out means for translating antenna designs to a form suitable for prototype fabrication, acquired RFID chips sufficient to demonstrate component independence[1], produced and tested genetically optimized RFID tag designs, obtained equipment and made modifications to its laboratory for prototype tag fabrication, and constructed software for Monte Carlo studies of its business case model.

The following section describes the status of each of the Phase I tasks in turn. For tasks in which technical work was completed in earlier reporting periods, the reader will be referred to the appropriate reports for the detailed technical descriptions of the work accomplished under that task.

2. Status of Phase I Tasks

Each task of the Phase I proposal will be described here, including its status at the end of the Phase I effort. When appropriate, the reader will be referred to the earlier Phase I reports for technical descriptions of the work accomplished.

2.1 Task1 — Antenna Design Sensitivity Study

This task was designed to address the sensitivity of relevant properties of an RFID antenna to small variations in antenna geometry and to dielectric loading ("detuning") of the antenna. The methodology employed was to use small changes in antenna geometry in NEC simulations and study the modeled antenna impedance, an important variable for the coupling of a passive RFID tag antenna to the RFID chip. Because antenna design is understood mathematically to be a "stiff" problem, *i.e.* small changes in parameters describing the problem lead to large changes in the resulting solution, it was expected that we would see significant changes in modeled antenna impedances. These expectations were confirmed and are described in detail in the first Phase I Report, CLIN-0001AA.

Sensitivity to dielectric loading was modeled by modeling an antenna located 8 mm above a layer of Delrin™, a plastic with a dielectric constant of 3.7. The forward gain reduction caused by the plastic layer was approximately 5 dB. Because passive RFID

[1] We now use the term "component independence" rather than our former usage of "component agnosticism". We believe that this terminology more accurately reflects the objective of freeing the design and fabrication of RFID tags from constraints of particular RFID chip technologies and vendors.

tags operate by backscatter, the impact on overall system performance could be expected to be 10 dB in this representative case. These results are reported in more detail in the first Phase I report, CLIN-0001AA.

2.2 Task 2 — Extension of Genetic Algorithm for RFID Antenna Design

Prior to beginning the Phase I effort, WTI had developed a proprietary genetic algorithm, GA_RV, for use as a design tool for development of antennas for passive RFID tags. Task2 of the Phase I effort involved extensions of GA_RV to address specific requirements for the Phase I effort:

1. The FOM (figure-of-merit) calculation in GA_RV was extended to include antenna footprint because the Phase I effort required antennas not to exceed a specified size (see below).

2. The FOM calculation was extended to optimize for matching to RFID chips with differing impedances, as required for the demonstration of "component independence" in the Phase I effort.

3. Procedures for accommodating different wire conductivities in GA_RV runs were established. This is necessary for the design of antennas using conductive ink rather than metals such as copper or aluminum. Conductive inks have significant potential for flexibility in production and rapid responsiveness to changes in end-user requirements as well as potential direct cost savings. Exploration of this potential in practical terms is important to the structure of the Phase I effort.

Further extensions to GA_RV made for the Phase I effort included inclusion of asymmetric dipole antennas, spiral antennas, and monopole antennas with counterpoise structures.

Each of the design geometries was considered in trial GA_RV runs. Folded symmetric dipoles and folded asymmetric dipoles were found to generate the most useful solutions for the design problems posed in the Phase I effort, and so further attention was restricted to those choices so as to keep the amount of testing within reasonable bounds for a Phase I effort.

2.3 Task 3 — Acquisition of RFID Chips

It was originally proposed that the Navy would provide the RFID chips for this project to insure that the choice of RFID chips was directed towards Navy requirements. This turned out to be impractical and WTI undertook to acquire RFID chips for this project. The initial round of RFID chip acquisition, reported in the second Phase I report, is as listed here:

1. WTI obtained fifteen (15) Alien Technologies (ST Micro) chips on straps.

2. Five (5) ATA559001-DBW chips were obtained from Atmel Corporation.

3. Four (4) EM4223 (V6) chips were obtained from EM Microsystems. These chips are mounted on copper foil straps.

Subsequently, it was determined that the Atmel parts were unsuitable for our purposes because they are not conventional 2-lead passive RFID chips, and so the Atmel parts were dropped from further consideration.

To substitute for the Atmel parts, we obtained a dozen ZumaRFID™ chips from Impinj. From the standpoint of proving the case of component independence, the choice of the ZumaRFID chip is desirable because it has significantly different impedance than other two RFID chips. Unfortunately, this chip was not available with attached straps, only as dies approximately 0.8 mm on a side, which introduces significant issues in fabrication of prototype RFID tags.

We decided not to evade this problem because production tags will not be constructed using chips with straps, and so it is desirable for WTI to begin to acquire skills in this type of fabrication as soon as possible. The approach taken to solve this problem is described in the description of the status of Task 5.

2.4 Task 4 — Genetic Algorithm Production Runs

In this section we show the results of genetic algorithm runs producing antenna designs for each of the chip sets used in the Phase I effort. Because the genetic algorithm necessarily depends on the operation of random processes, several runs were made for each choice of chip, geometry, and choice of conductor (copper or conductive ink) and the best result, based on FOM, was picked for fabrication.

The conductive ink used in this project has a relatively high conductivity of 3.3×10^6 S/m, *i.e.* about (1/20)× the conductivity of copper. The conductive ink (and other materials) will be discussed further in the description of the fabrication task following, and data sheets for all materials are included as an appendix.

The images here reflect the fabrication process used to produce the antennas. All genetic algorithm runs yield a NEC input deck corresponding to that antenna. WTI has produced a software converter that translates a NEC input deck into a corresponding DXF file, which is then manipulated to produce an image used in antenna fabrication. Copper etch antennas are produced by a photo-etch process (see description of task following) and so the photograph negative image used in the photo etch image is shown. Conductive ink antennas were made directly from the DXF files, and so images of the CAD file are shown.

All antennas were constrained to lie within a 2 inch × 3 inch footprint. This is not a fundamental limit, so the same tools can be used to design smaller antennas (if desired), subject to the usual physical constraints that limit antenna efficiency as size is reduced. Because these antennas are inductively self-loaded by virtue of their shape (as folded dipoles), some of the antennas did not require the full allowed area and the maximum linear dimension of each antenna is indicated in the caption.

Typical genetic algorithm runs involved a population of 512 antennas and ran from 60 to 500 generations. Literally hundreds of thousands of antennas were generated by the genetic algorithm runs (and of course most discarded in the process) and so a systematic nomenclature for antennas was important. Antennas were stored in directories indicating the chip type and antenna geometry and conductor material, *e.g.* 'Alien\cu_dipole1\ga285_141.dat'. The filename indicates the antenna in the 285th generation and the 141st individual. Software tools were produced for automatically winnowing through the large number of candidate antennas to identify the antennas of interest.

Note that almost all these antennas have bends which give the antenna an inductive reactance that compensates for the capacitive reactance of the RFID chip. This results from the action of the genetic algorithm to achieve the a low VSWR between the RFID chip and antenna to obtain optimal tag performance.

2.4.1 Alien Technologies/ST Micro Genetic Algorithm Results

The impedance of the Alien Technologies/ST Micro RFID chip (with strap) is $17 + j\,149\,\Omega$. We first show antennas chosen for fabrication in copper etch.

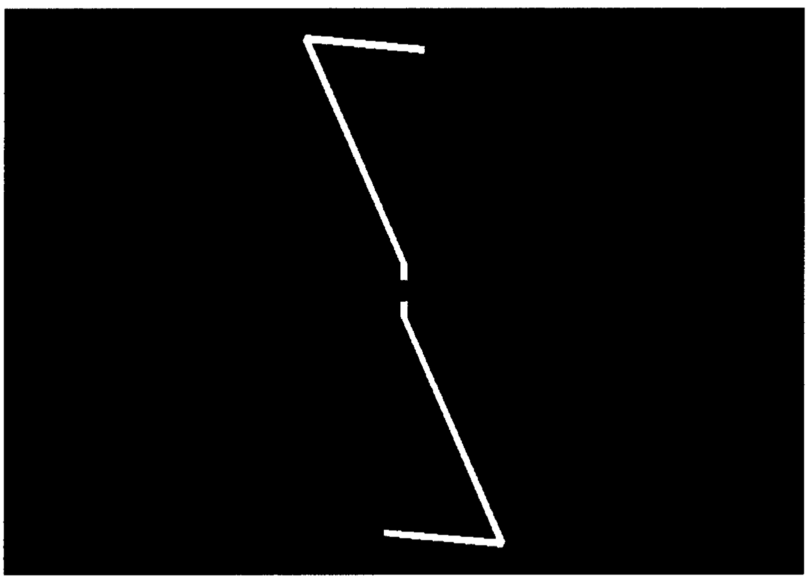

Figure 1: Antenna Alien\cu_dipole2\ga059_376. The antenna is 3 inches long.

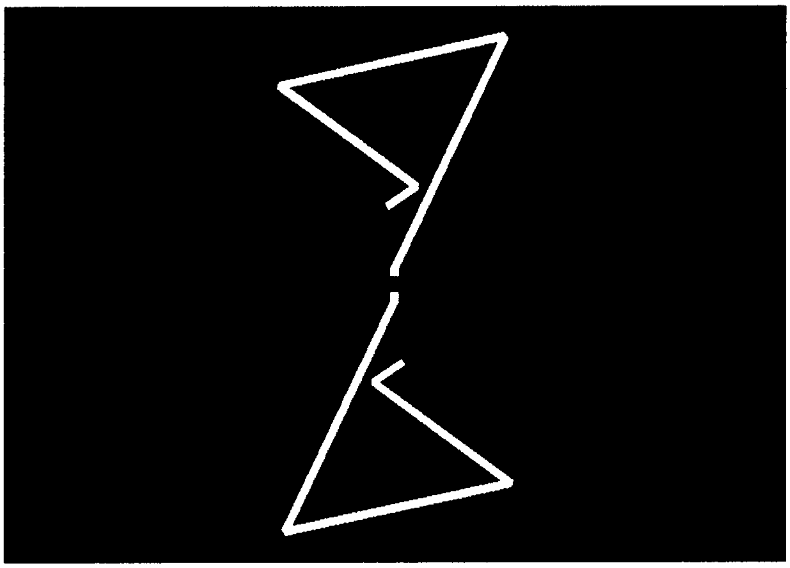

Figure 2: Antenna Alien\cu_dipole3\ga284_343. Antenna is 2.45 inches in the y-direction.

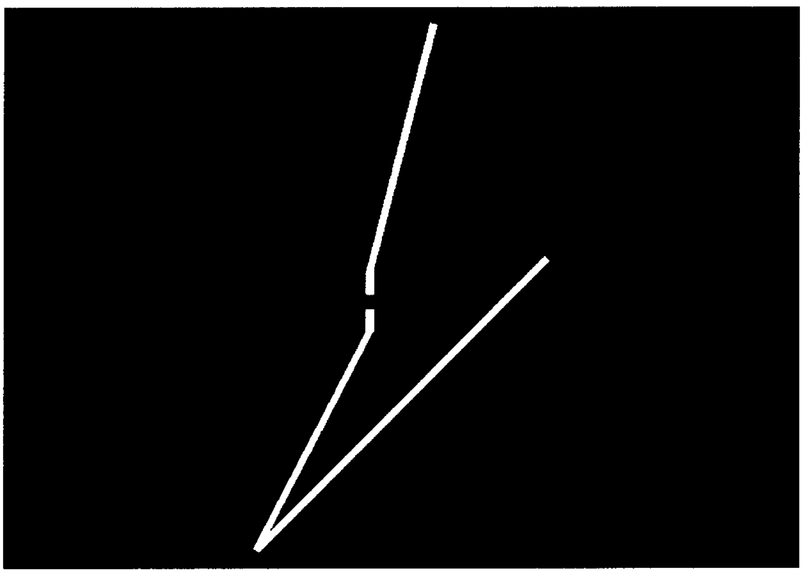

Figure 3: Antenna Alien\cu_asymm2\ga299_386. An asymmetric dipole extending 2.85 inches in the y-direction.

The following antennas were selected for fabrication from conductive ink.

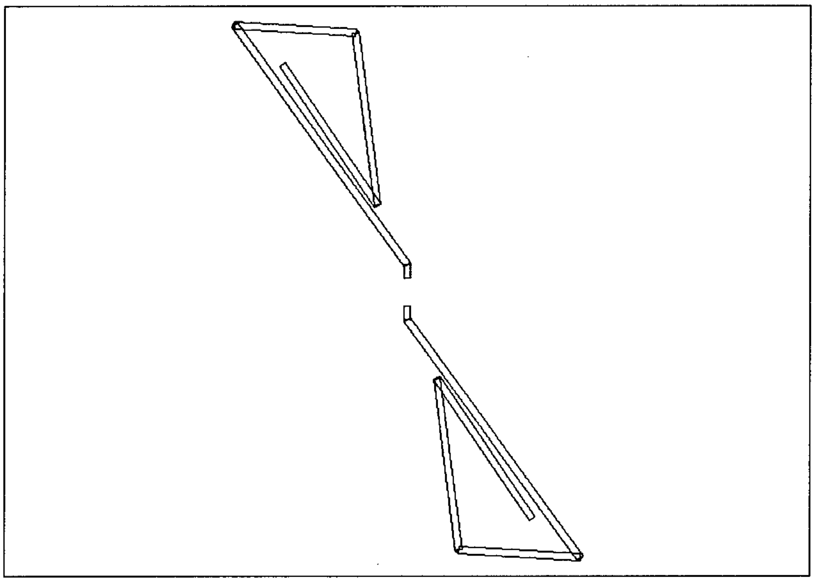

Figure 4: Antenna Alien\ink_dipole3\ga210_289. A symmetric dipole antenna extending 3 inches in the y-direction.

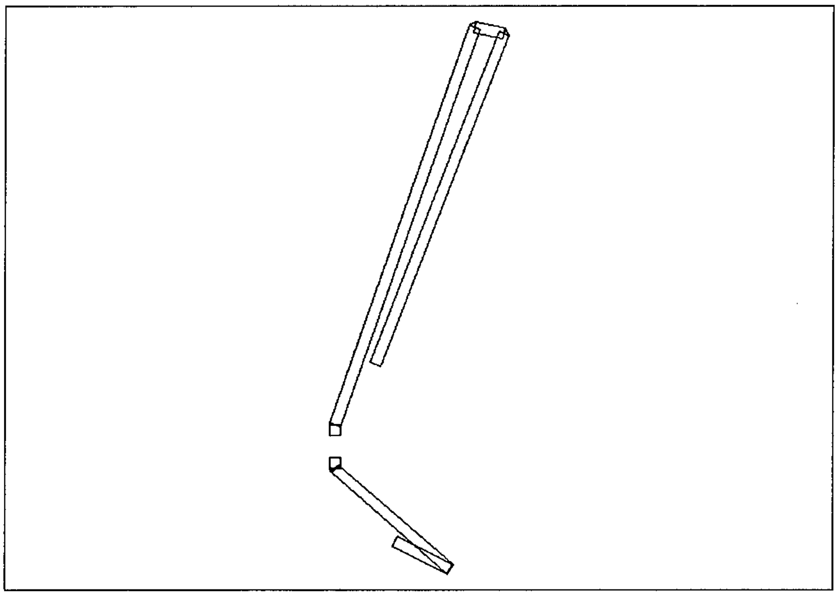

Figure 5: Antenna Alien\ink_asymm4\ga378_454. An asymmetric dipole antenna extending 1.97 inches in the y-direction.

2.4.2 EM Micro Genetic Algorithm Results

The impedance of the EM4223 RFID chip is $23 + j\,376.5\,\Omega$. We first show antennas chosen for fabrication in copper etch.

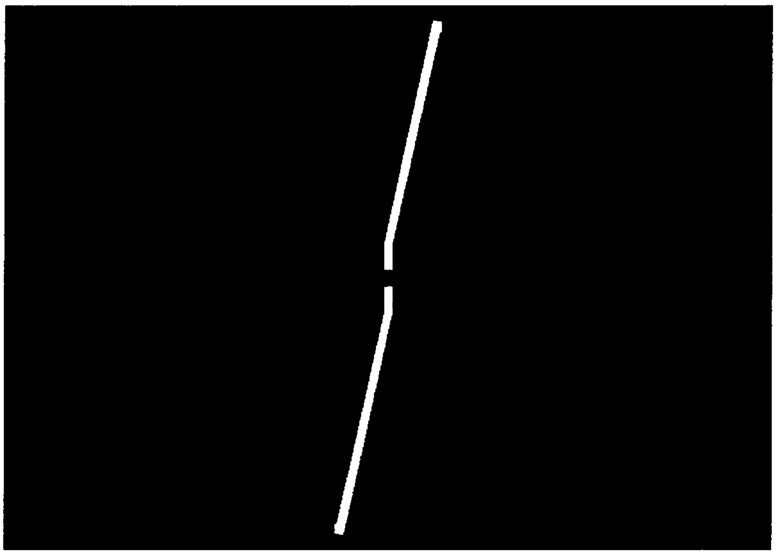

Figure 6: Antenna EM\cu_dipole2\ga049_396. This antenna is very nearly a simple dipole extending 2.38 inches in the y-direction.

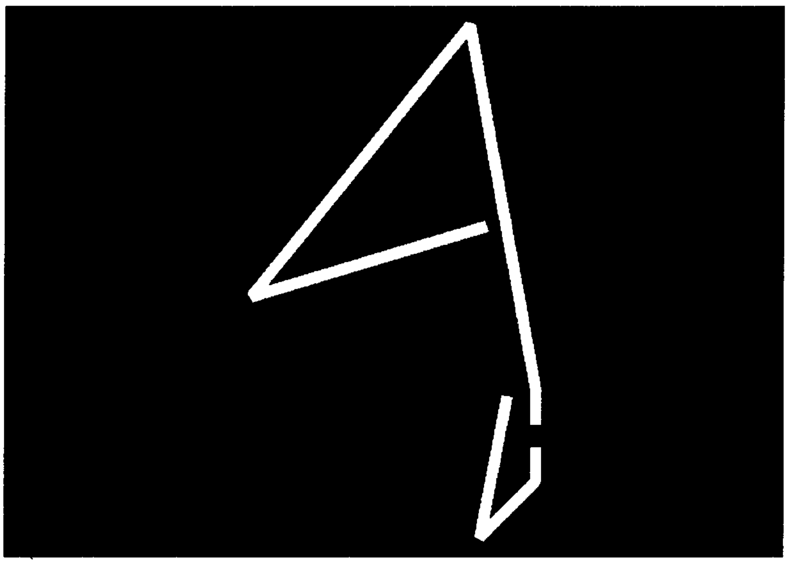

Figure 7: Antenna EM\cu_asymm1\ga115_409. This antenna extends 1.81 inches in the y-direction.

The remaining antennas in this section are antennas for the EM4223 chip fabricated from conductive ink.

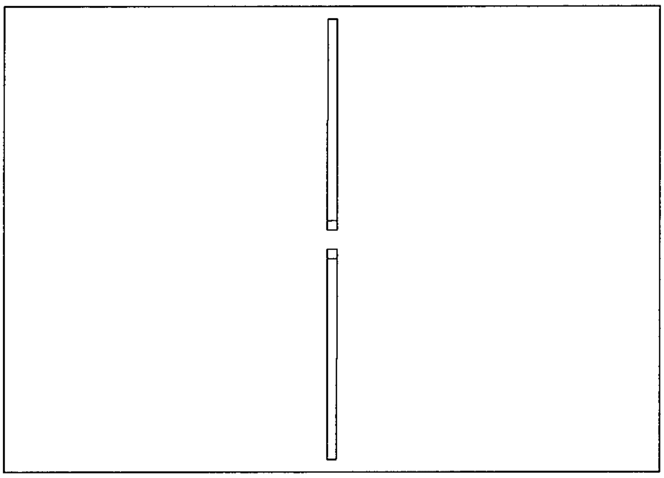

Figure 8: Antenna EM\ink_dipole1\ga009_419. The optimal antenna in this case is a simple dipole 1.82 inches in length.

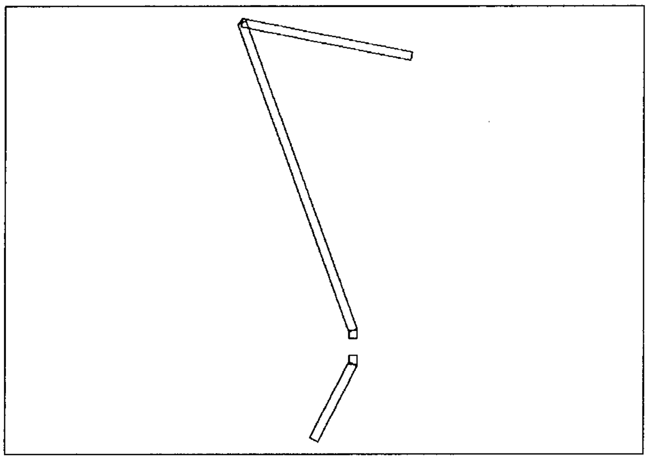

Figure 9: Antenna EM\ink_asymm3\ga124_338. An asymmetric dipole extending 1.77 inches in the y-direction.

2.4.3 Impinj Genetic Algorithm Results

The impedance of the Impinj ZumaRFID chip is $65 + j\,108\,\Omega$. We first show antennas chosen for fabrication in copper etch.

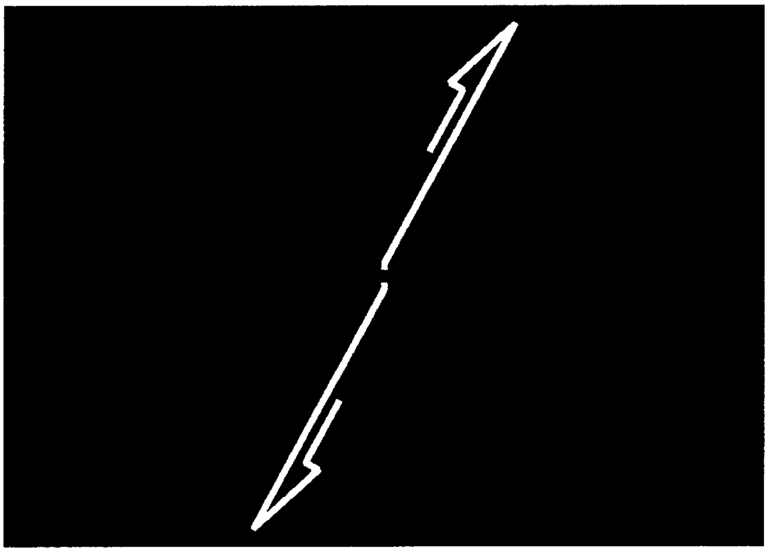

Figure 10: Antenna Impinj\cu_dipole1\ga083_476. This antenna extends 3 inches in the y-direction.

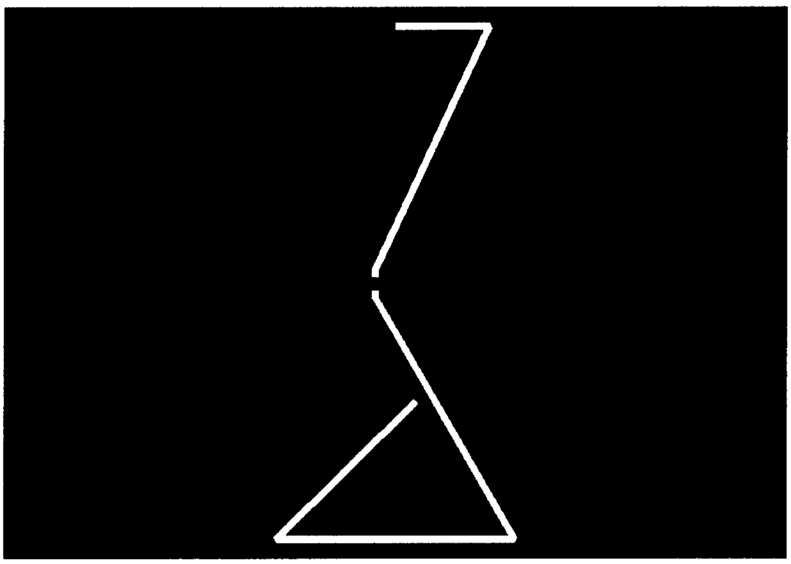

Figure 11: Antenna Impinj\cu_asymm3\ga035_498. This antenna has an overall length of 3 inches.

The remaining antennas in this section are antennas for the Impinj ZumaRFID chip fabricated from conductive ink.

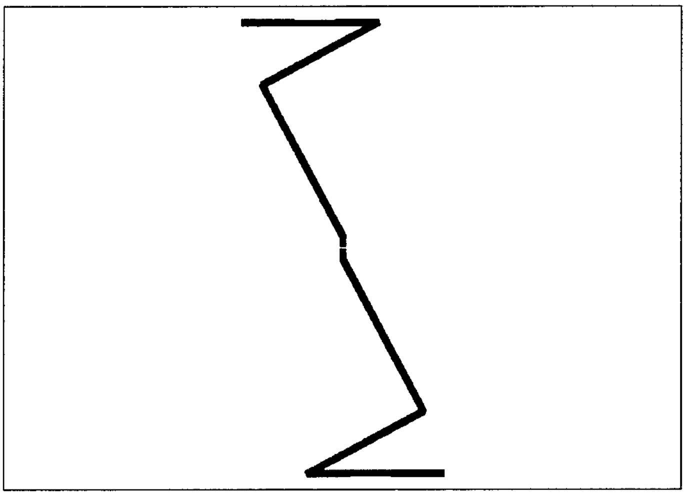

Figure 12: Antenna Impinj\ink_dipole2\ga530_460. A symmetric dipole antenna extending 3 inches in the y-direction.

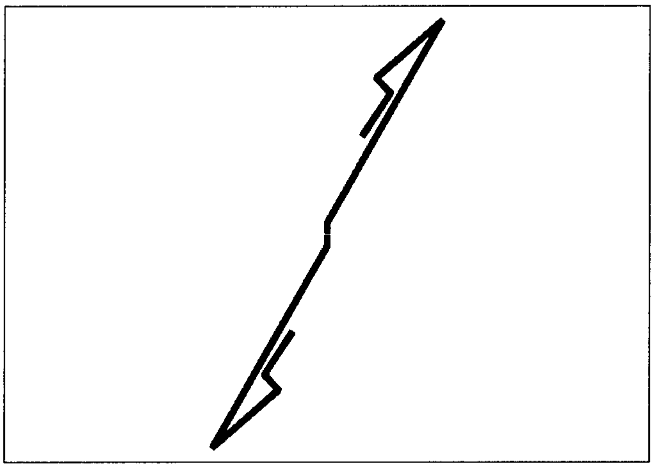

Figure 13: Antenna Impinj\ink_dipole3\ga284_260. A symmetric dipole antenna extending 2.94 inches in the y-direction.

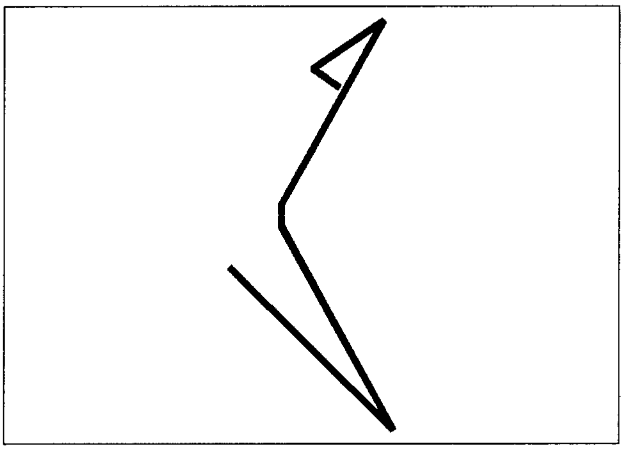

Figure 14: Antenna Impinj\ink_asymm5\ga089_256. An asymmetric dipole extending 2.85 inches in the y-direction.

2.5 Task 5 — Fabrication of Prototype RFID Tags

2.5.1 Fabrication of Copper-Etch Antennas

Copper etch antennas for this project were made from conventional PC production boards with a single layer of copper. The boards were made of FR4, a standard RF substrate with a low loss tangent at low GHz frequencies. Standard test boards for the prototype antennas were cut out of the FR4 PC boards to a standard 3 inch × 4 inch size for convenience. Resist patterns were put on the test boards using standard photo-fabrication techniques and the boards were then etched using ferric chloride etch in WTI's laboratory.

2.5.2 Fabrication of Conductive Ink Antennas

A conductive ink with unusually high conductivity (3.3×10^6 S/m bulk conductivity) was identified available through a local supplier, Creative Materials, Inc., in Tyngsboro, MA. This ink, 112-15, is described in the data sheet included as Appendix 1.

Ordinarily, prototype RFID antennas from this conductive ink would be made using a screen printing process and we anticipate that this will be done in future prototyping efforts. Unfortunately, there was not sufficient time left in the Phase I project at the completion of the genetic algorithm runs to pursue this mode of production. Creative Materials provided to WTI samples of the 112-15 conductive ink printed on a Mylar™ substrate so that the conductive ink antennas could be cut out by hand. Electrical testing of these antennas showed that these hand-produced antennas were sufficiently close to desired electrical properties to proceed to the next stages of fabrication and testing.

2.5.3 Attachment of RFID Chips

The Alien Technologies/ST RFID chips and the EM4223 RFID chips had straps attached to the chips that significantly simplified the problem of chip attachment to the RFID antenna. A silver-loaded conductive epoxy developed by Creative Materials was used for this purpose, GPC-251. The data sheet for GPC-251 is included as Appendix 2.

Direct attachment of Impinj chips without straps (*i.e.* the 0.8 mm × 0.8 mm die) requires a different technique because conductive epoxy cannot be applied with sufficient precision that an isolated conduction path is made from the antenna pads on the chip to the corresponding arms of the RFID antenna. This is particularly true for hand fabrication of a prototype RFID antenna. The appropriate technique, suitable in principle for hand fabrication and scalable to large scale manufacture, is to use an anisotropically conductive adhesive, such as Creative Materials 112-05. The data sheet for 112-05 is included as Appendix 3. The anisotropically conductive adhesive has, upon curing, a high conductivity perpendicular to the surface to which it has been applied and a low conductivity perpendicular to the high conductivity direction. Thus, a layer of the anisotropically conductive adhesive can be applied over the two terminals of the antenna, which are separated by an appropriate distance (say 0.4 mm for the Impinj prototype RFID tag design) and will not short out the antenna. Then the RFID chip can be applied to the adhesive face down (so that the antenna pads are in contact with the anisotropically conductive adhesive) with the antenna pads vertically above their respective contact points on the antenna. A conduction path is then available from the antenna pads into the RFID chip without shorting the two antenna contact points together.

Unfortunately, we were unable to work out a procedure for attaching the Impinj RFID chips with the anisotropically conductive adhesive because the material is sensitive to issues in surface preparation, the temperature of heating prior to chip attachment, and the pressure applied while the assembly cools. We have communicated our difficulties to Creative Materials which has agreed to work with us in the near future to develop a workable chip attachment procedure. Also, we understand that improved anisotropically conductive materials are currently under development which should have wider tolerances for fabrication procedures.

2.6 Task 6 — Testing of Prototype RFID Tags

2.6.1 Overview of Testing Procedure

As originally proposed and as discussed in the 2 March 2005 site visit, we had planned to use testing in the 3 m anechoic chamber as a proxy for read range testing. The feedback we got in the meeting indicated that direct read range testing would be desirable because it is more readily interpretable in terms of actual system performance. At the time of the original proposal, commercially available 915 MHz RFID tag readers were relatively expensive and difficult to obtain, but that situation has changed markedly at present. I discussed with Mr. McEntee the possibility of doing direct read range testing in mid-June and that approach has been adopted for Task 6. Direct read range testing obtains the data which Task 6, as originally formulated, would have obtained indirectly.

Bench testing of antennas with a network analyzer was carried out to verify that the electrical properties of the antennas were in correspondence with the results of the NEC modeling in the genetic algorithm. Antenna testing in the anechoic chamber will also remain an important part of completing product development of RFID tags and plays a prominent role, together with bench testing and read range testing in the proposed Phase II effort.

WTI has obtained a SAMsys MP9320 2.7 EPC™ tag reader for use in the direct read range testing. This reader has a linearly polarized antenna and radiates 1 W. Linear polarization is most directly relevant to the operation of our folded dipole and asymmetric folded dipole antennas. Read ranges were determined in free space by measuring the number of reads obtained in a 60 second test period. Care was given to avoid dielectric loading of the antennas during read range testing.

2.6.2 Testing of Alien Technologies/ST RFID Tags

We show first plots of read range tests with the prototype tags using Alien Technologies/ST RFID chips.

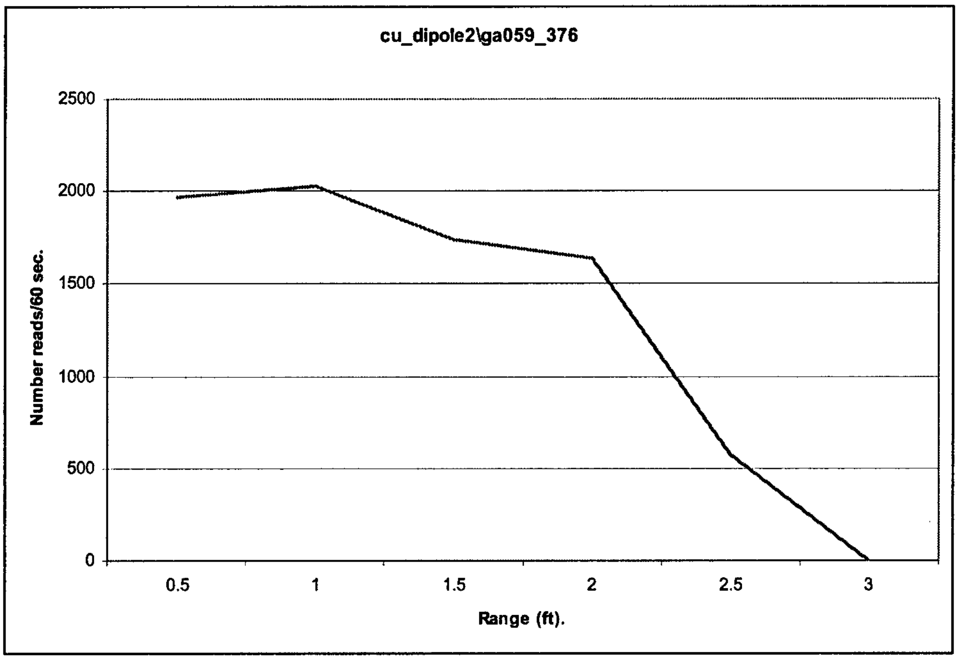

Figure 15: Tag read counts in 60 second test interval vs. read range for prototype tag cu_dipole2\ga059_376. The maximum effective read range is between 2.5 and 3 feet.

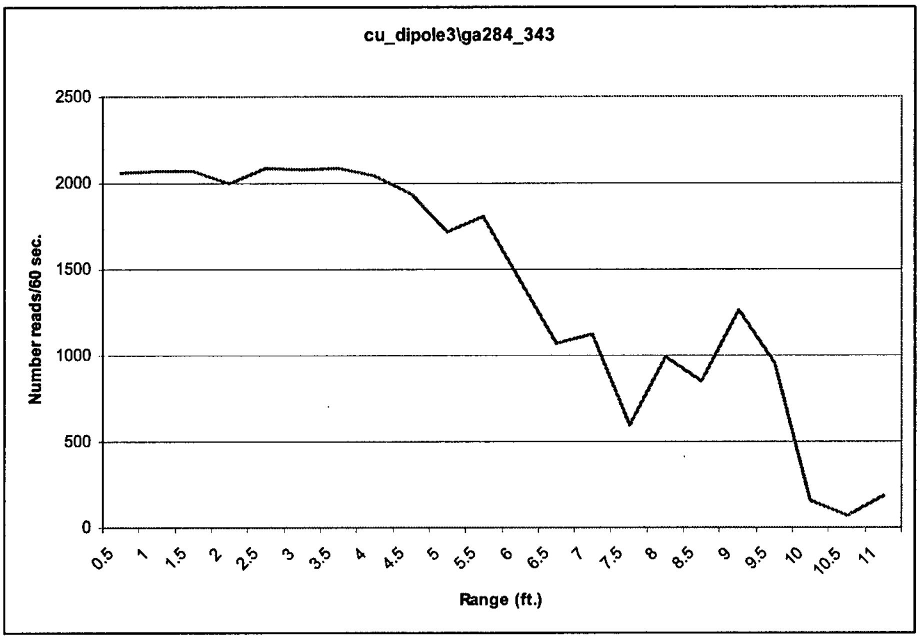

Figure 16: Tag read counts in 60 second test interval vs. read range for prototype tag cu_dipole3\ga284_343. This tag is performing in a fashion consistent with model predictions for a maximum effective read range over 11 feet.

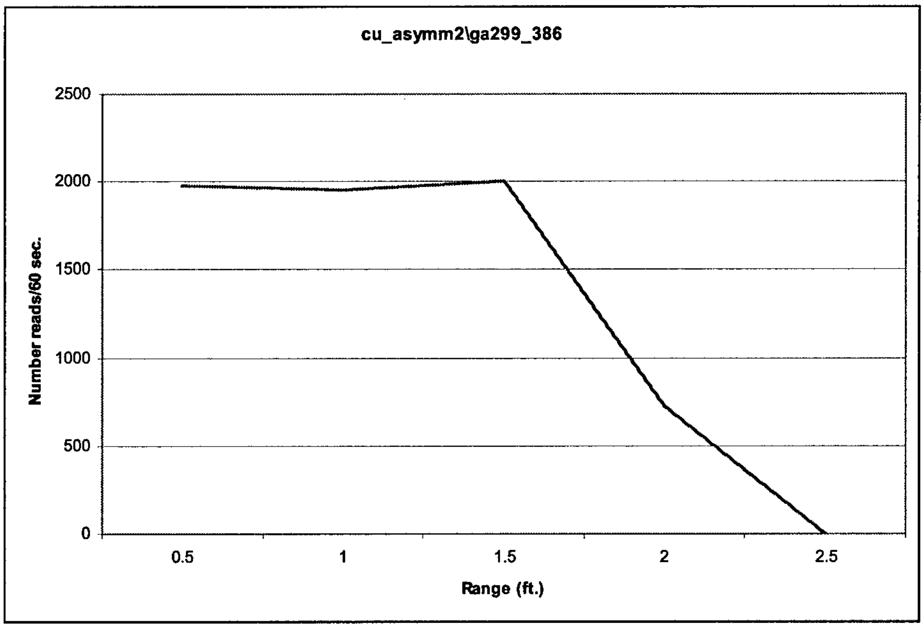

Figure 17: Tag read counts in 60 second test interval vs. read range for prototype tag cu_asymm2\ga299_386. The maximum effective read range for this prototype tag is between 2.5 and 3 feet.

We were encouraged by the read range results obtained from the tag cu_dipole3\ga284_343, which were approximately in line with model predictions, but puzzled by the smaller effective read ranges for the other two copper etch tags. Since the tags matched their electrical modeling reasonably well, we began to suspect a problem with the attachment of the RFID chips to the tag antennas. We had on hand a pair of separate prototype RFID antennas for a commercial product under development at WTI, one of which had an Alien Technologies/ST RFID chip with strap attached by electrically conductive epoxy. We attached a chip to the other antenna using adhesive tape (not intended as a manufacturing procedure!) which gave us an effective "press-fit" between the chip and the antenna. Although the antenna with an adhesive attached RFID chip was a little temperamental, it routinely performed with three to four times the read range of the prototype RFID tag with chip attached with electrically conductive epoxy.

This test conclusively proves that the attachment of the RFID chip to the antenna using the conductive epoxy can degrade the read range performance of our prototype tags. Our best result shows that the conductive epoxy can in principle perform up to expectations, but its performance is not consistently reliable as currently applied. We are making arrangements with Creative Materials to institute procedures leading to proper application of its conductive epoxy to achieve consistent performance.

A photograph of our most successful tag, cu_dipole3\ga284_343 is included below in Figure 18.

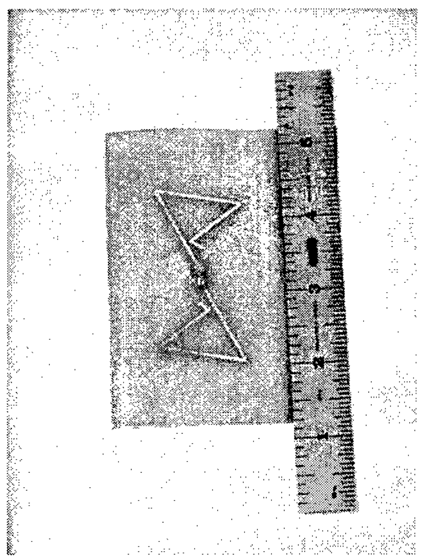

Figure 18: Prototype tag Alien\cu_dipole3\ga284_343 which exhibited maximum read range performance in excess of 11 feet. The tag is a symmetrical dipole inductively self-loaded for impedance matching to the RFID chip. The RFID chip has attached straps which are used to fasten the chip to the antenna with electrically conductive epoxy. Note that the RFID and strap assembly is mounted face down on the antenna. The antenna is a copper etch pattern on a piece of FR4 circuit board.

Testing of the two tags made with conductive ink and Alien Technologies/ST RFID chips showed the tags to be functional, but with minimal read range. It seems likely that surface preparation is the key issue for proper performance of the conductive epoxy and that surface preparation is even more important for the surface of conductive inks. One possibility suggested by Creative Materials for future investigations of surface preparation is cleaning with MEK (methyl ethyl ketone).

2.6.3 Testing of EM 4223 RFID Tags

All of the prototype tags constructed with EM 4223 RFID chips, both with copper etch antennas and with antennas made from electrically conducting ink, were functional in read range testing. Read ranges obtained were intermediate between those obtained with the Alien Technologies/ST prototype tags made from copper etch and those made with conductive ink. Results are consistent with our observations made above on the importance of surface preparation for proper performance of the electrically conductive epoxy.

Read rates were nearly constant until they fell off dramatically as range was increased, so the maximum effective read range is reported below in tabular form.

Tag Name	Read Range (inches)
cu_dipole2\ga049_396	16
cu_asymm1\ga115_409	13
ink_dipole1\ga009_419	8
ink_asymm1\ga171_271	10

Table 1: Maximum effective read range for prototype tags constructed using EM 4223 RFID chips. Performance of the electrically conductive epoxy is an issue for the read range performance of these tags as well.

2.7 Task 7 — Techniques to Include Dielectric Loading in Genetic RFID Antenna Design

NEC-4 can model antenna performance in proximity to an infinite half-space with a specified dielectric constant and conductivity. This capability is achieved by including a control card in the NEC control file as shown below. This limited ability to model dielectric loading is actually sufficient to treat many cases of interest because dielectric loading effects are primarily due to material within one wavelength of the antenna, so the presence or absence of material beyond that distance is mostly irrelevant, except as it pertains to the complexity of the mathematical formulation of the electromagnetic simulation.

If a more accurate treatment of dielectric loading is desired, a geometric specification of the geometry of dielectric and/or magnetic material in proximity to the antenna is required. At that level of sophistication, an electromagnetic simulation tool such as IE3D produced by Zeland Software will have to be used. An appropriate interface for automated operation of an electromagnetic simulation package such as IE3D will have to be developed so that it may be used as the electromagnetic evaluation tool in a genetic algorithm of the type used by WTI for genetic RFID antenna design.

```
CE conductive ink RFID
GW 1, 1,  0.00968, -0.01403,  0.00800, 0.00884, -0.04303,  0.00800, 0.001000
GW 2, 1,  0.00884, -0.04303,  0.00800, 0.00000, -0.00400,  0.00800, 0.001000
GW 3, 1,  0.00000, -0.00400,  0.00800, 0.00000,  0.00400,  0.00800, 0.001000
GW 4, 1,  0.00000,  0.00400,  0.00800,-0.00884,  0.04303,  0.00800, 0.001000
GW 5, 1, -0.00884,  0.04303,  0.00800,-0.00968,  0.01403,  0.00800, 0.001000
GE 0
EX 0,3,1,0,1,0,0,0
LD 5,0,0,0,5.7e7
FR 1,1,0,0,920.0,1.0
GN 2,0,0,0,3.700000,0.0
EK 0
RP,0,36,36,1011,0.0,0.0,2.57,10.0
EN
```

Figure 19: Example NEC-4 control file showing inclusion of an infinite dielectric half space with dielectric constant of 3.7. Location and dielectric constant of the dielectric load is controlled by the "GN" card.

2.8 Task 8 — Monte Carlo Studies Demonstrating Robustness of Business Case

The Phase I proposal showed a business case illustrating cost savings achieved by "component independence" (called "component agnosticism" in the proposal), the ability to always buy the cheapest available RFID chips because of the ability to design antennas to match those chips with rapid and flexible turn-around. The business case shown in the Phase I proposal was computed "by hand" and the need for a tool to investigate the model and test assumptions in a less intensive fashion was apparent.

We have produced a *Mathematica*™ model that carries out the model calculation. As in the original calculation, 9 companies are in competition in the production of RFID chips, but the duration of the simulation runs for a longer interval, 72 periods which can be considered as one month each. Nominal utilizations, adjusted total costs, marginal costs, and cost of capital are controlled by lists of entries in the *Mathematica* notebook. Thresholds controlling the prices at which RFID chips can be offered by the competing producers can be adjusted. The utilization of production facilities of the competing companies is modeled as a Markov random process in which successive steps are Gaussian-distributed random variables with specified standard deviation. The variation of utilization of production facilities is limit-stopped at 0 and 1 so as not to yield nonsensical results.

The *Mathematica* notebook is set up to run some number of instances, say 1000, with different random numbers applied and display the results. Graphical displays of pricing data and production utilization are also generated.

The component independence business strategy is seen to be robust and effective under a broad range of parameters as described above. A copy of the *Mathematica* notebook will be supplied upon request.

2.9 Task 9 — Report of Phase I Results

This report constitutes completion of Task 9 of the Phase I Proposal.

3. Summary of Phase I Accomplishments

We list here the specific technical accomplishments of WTI's Phase I effort:

1. Demonstration of the sensitivity of antennas used in RFID tags to small changes in antenna geometry.

2. Demonstration of the sensitivity of RFID tag antennas to dielectric loading.

3. Extension of WTI's proprietary genetic algorithm for the design of RFID antennas to include constraints in antenna footprint, impedance of the RFID chip, and varying antenna material conductivities.

4. Extension of WTI's proprietary genetic algorithm to include new antenna geometries.

5. Acquisition of suitable RFID chips for studies of component independence (formerly called "component agnosticism").

6. Automated design, using the genetic algorithm, of RFID antennas specific to three different RFID chips and made both from copper etch and conductive ink, thus demonstrating the technical viability of component independence.

7. Production of program antennas in copper etch and with electrically conductive ink.

8. Demonstration of functioning RFID tags of a wide variety of designs. One of these tags exhibited a large read range, showing that large read range is obtainable in practical circumstances.

9. Identification of materials issues in the performance of conductive adhesives currently limiting read range and strategies for addressing these issues.

10. Identification of a software development path allowing incorporation of dielectric loading effects on RFID tags in WTI's genetic algorithm for RFID tag design.

11. Development of a *Mathematica* notebook for Monte Carlo simulations of the component independent business case allowing examination of cost saving obtained under a wide variety of model assumptions and statistically varying parameters.

4. New Issues to Address in Phase I Option

The last stages of the Phase I effort have identified several new problems that must needs be addressed to move forward with development of low-cost, flexibly-manufactured RFID tags using the techniques being developed. Fortunately, the strategies for addressing these new problems are clearly defined, and there is an excellent prospect for speedily finding solutions.

The most pressing problems impacting RFID tag performance, specifically read range, and RFID tag fabrication are connected with the performance and proper use of electrically conducting adhesives. Problems have been identified both in the electrically conducting epoxy used for fabricating prototype RFID tags when the RFID chip is available with a strap and in the anisotropically conductive adhesives contemplated for attaching RFID chip dies directly to antennas, as required for low-cost production in high volume. It is likely that in both instances, much of the solution involves proper preparation of surface, though the anisotropically conductive adhesive also has constraints in temperature and pressure in application. Because the supplier of these conductive adhesives is local to WTI, we have arranged to work directly in their laboratory to facilitate the necessary technology transfer to WTI for proper use of these products. As a fall-back position, WTI will also investigate alternate sources of supply of equivalent conductive adhesives.

Owing to the critical path nature of these problems (although a suitable technical solution is confidently expected), it may be appropriate to adjust the Statements of Work for the Proposed Phase I Option and Phase II to reflect addressing materials performance issues together with related testing of new RFID tags incorporating these procedural improvements early in the upcoming development efforts (if funded). WTI is prepared to negotiate such adjustment with the Navy if desired.

5. Conclusions and Recommendations

The Phase I development program undertaken by WTI has demonstrated design and operation of RFID tags using genetic algorithms in support of a methodology we term "component independence". This will allow RFID tag consumers to purchase RFID tag components, principally RFID chips, on a flexible lowest-cost basis and incorporate them in RFID tags by adjusting the antenna design appropriately to the electrical properties of the RFID chip (and the electrical properties of the object being tagged). Use of conductive ink based antenna designs, when appropriate, will give added flexibility in production with attendant savings over the product development cycle.

The next phases of this work, as proposed, will address materials properties crucial to tag performance, cluster computing techniques to accelerate the genetic algorithm design process, and the development and management of a database of RFID tag designs further increasing the ability to rapidly produce high performance RFID tags for a variety of applications. Specific tag developments planned building on these techniques in the proposed Phase II effort will be tags designed to operate despite loading ("detuning") by proximity to dielectric and/or magnetic materials and a passive RFID tag design for operation on the surface of metal containers. These new tag designs, together with more advanced tag designs along the lines already explored, will address a wide variety of Navy logistics requirements.

Prospects for commercialization of these design methodologies are particularly bright because WTI is already beginning design of commercial RFID tags using these techniques.

We strongly believe that diligent pursuit of the development program underway and as proposed will yield large returns both for Navy logistics and in the commercial realm.

Appendix 1 — Conductive Ink Materials Data Sheet

CREATIVEMATERIALS

Creative Materials, Inc.

141 Middlesex Road T 978.649.4700
Tyngsboro, MA 01879 F 978.649.2040

112-15

EXTREMELY CONDUCTIVE INK

DESCRIPTION: 112-15 is an ink/coating with extremely high electrical conductivity for application by screen-printing, dipping and syringe dispensing. The product features excellent adhesion to Kapton, Mylar, glass and a variety of other substrates. **The superior conductivity of this product allows the end user to print narrower and/or longer circuit trace lines without compromising overall maximum ohm values.** The proper use of this feature can result in a significant cost saving. Unlike conventional conductive materials, this product is very resistant to abrasion, scratching, flexing and creasing. Some applications for 112–15 include, but are not limited to, emi/rfi shielding of polyimide flexible circuits, polymer thick film circuitry, membrane switches and coatings for tantalum capacitors.

TYPICAL PROPERTIES:

Viscosity (cps) 28,000 – 30,000

Filler Silver

Percent Silver (cured) > 84

Crease Resistance Excellent

Volume Resistance, max. (Ω-cm) 0.00003

Sheet Resistivity (Ω/square/mil) 0.010

Hydrolytic Stability Excellent

Useful Temperature Range (°C) -55 to 200

SUGGESTED HANDLING & CURING: 112-15 is ready to use as supplied. Further thinning may be accomplished by adding small amounts of CMI thinner #112-18, #112-19 and/or #105-36. Prior to use, be certain to mix well to resuspend silver. **Best properties** for most applications, result when cured for 3 to 5 minutes at 110°C. Excellent properties are also obtained on a variety of substrates by curing at temperatures ranging from 50°C to 175°C. End user is advised to experimentally determine temperature and time best suited for individual applications.

STORAGE: Shelf life: 2 months at 25°C; or 6 months at 5°C; or 12 months at -10°C.

SAFETY & HANDLING: Use with adequate ventilation. Keep away from sparks and open flames. Avoid prolonged contact with skin and breathing of vapors. Wash with soap and water to remove from skin.

All technical information is based on data obtained by CMI personnel and is believed to be reliable. No warranty is either expressed or implied with respect to suitability in a particular application or possible infringements on patents.

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Appendix 2 — Conductive Epoxy Materials Data Sheet

CREATIVEMATERIALS

www.creativematerials.com

ISO 9001 CERTIFIED

Creative Materials, Inc.
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GPC 251

ELECTRICALLY CONDUCTIVE EPOXY ADHESIVE

DESCRIPTION: GPC 251 is a two part, room temperature curing, silver filled epoxy adhesive. System is designed to be used for making electrical and mechanical attachments on electrical components and devices. Unlike typical room temperature curing systems, this product always results in excellent conductivity and is less sensitive to handling and ambient conditions.

	Part A	Part B
Appearance:	Silver	Light Yellow
Consistency:	Paste	Liquid
Mix Ratio (by weight):	100 (17)	5.9 (1)
Pot Life:	-----	60 minutes

MIXING INSTRUCTIONS: Premix Part A in original container prior to adding curing agent. Add Part B to Part A and mix until uniform.

CURING INSTRUCTIONS: Best results are obtained when product is cured at one of the following schedules:

24 hours @ 25°C, or
60 mins @ 65°C, or
30 mins @ 95°C, or
5 mins @ 120°C

TYPICAL CURED PROPERTIES:

Volume Resistivity, max. (25°C)	0.005 Ω-cm
Volume Resistivity, max. (120°C)	0.0002 Ω-cm
Tensile Shear (psi)	>1800
Water Absorption (%)	< 0.06
Tensile Strength (psi)	11,200
Solvent Resistance	Excellent
Solderable	No
Specific Gravity	2.7
Thermal Conductivity (BTU/ft^{2}hr°F/ft)	3.9

STORAGE: Shelf life Parts A and B: 12 months in unopened, unmixed containers.

All technical information is based on data obtained by CMI personnel and is believed to be reliable. No warranty is either expressed or implied with respect to results or possible infringements on patents.

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Appendix 3 — Anisotropically Conductive Adhesive Materials Data Sheet

CREATIVEMATERIALS

Creative Materials, Inc.
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ISO 9001 CERTIFIED

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112-05

ANISOTROPIC CONDUCTIVE THERMOPLASTIC ADHESIVE

DESCRIPTION: 112-05 is screen-printable, anisotropic, conductive hot melt adhesive. This product features excellent adhesion to Kapton, Mylar, glass and a variety of other substrates. Unlike conventional conductive materials, this product is very resistant to flexing and creasing. The product can be rebonded many times by simply adding heat and slight pressure. Applications for 112-05 include, but are not limited to, conductive splicing of ribbon cables, PTF circuits, and electrical attachment of surface mounted devices. This product is useful in application where shorts between closely spaced contacts is a concern. 112-05 is a screen-printable version of 111-29.

TYPICAL CURED PROPERTIES:

Volume Resistivity (Ω-cm)	
(X, Y Axis)	1×10^{12}
(Z Axis)	0.0001
Consistency	Smooth paste
Crease Resistance	Excellent
Hydrolytic Stability	Excellent
Useful Temperature Range (°C)	-55 to 140
Thermal Stability (°C)	Good to 220
Peel Strength (lbs./inch)	9 - 11

HANDLING & CURING: 112-05 is ready to use as supplied. Further thinning may be accomplished by adding small amounts of CMI Thinner # 113-12. Apply thin film of adhesive to one or both surfaces to be bonded. Apply adhesive to a total dry thickness of 0.6 - 1.3 mils. Dry at room temperature for approximately 30 to 40 minutes, or 1-3 minutes at 120°C. Place the two surfaces together and cure in a heat-sealing press for 5-7 seconds @ 175°C using 100 - 150 psi to hold the surfaces tightly together. End user is advised to experimentally determine pressure, temperature and time best suited for individual applications. (See back of sheet for step-by-step directions.)

STORAGE: Shelf life: 2 months at 25°C; or 6 months at 5°C; or 9 months at -10°C.

SAFETY & HANDLING: Use with adequate ventilation. Keep away from sparks and open flames. Avoid prolonged contact with skin and breathing of vapors. Wash with soap and water to remove from skin.

SUGGESTED PROCEDURE FOR APPLYING 112-05

1. As with all adhesive bonds, surface preparation is a vital part of the process Carefully clean both surfaces to be bonded with MEK if possible. If MEK is not compatible with the surfaces to be bonded, another suitable solvent may be substituted.
2. Allow cleaned surfaces to dry for approximately 2-3 minutes.
3. Apply CMI#112-05 to both surfaces to be bonded by means of a suitable technique (i.e. screen-printing, syringe dispensing, brushing, spraying, etc.). The thickness range for good bonding is typically 0.6 mils to 1.3 mils for most surfaces, but is influenced by the geometry of the surfaces. The end user is encouraged to experimentally determine the best thickness for each individual application.
4. Allow CMI#112-05 to dry at room temperature until it is tack-free to the touch. (A slightly elevated temperature may be used if needed.) The time will vary depending on the thickness, but usually is approximately 30-40 minutes. 112-05 can also be dried for1-3 minutes at 120°C.
5. Place the two surfaces together and cure in a heat-sealing press for 5-7 seconds @ 175°C using enough pressure (100 - 150 psi) to hold the surfaces tightly together. End user is advised to experimentally determine pressure, temperature and time best suited for individual applications.
6. Allow to cool to room temperature under the same pressure.
7. Remove pressure. Part is ready for use.

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Wavelet Technologies, Inc. developed and applied electromagnetic design techniques making RFID tag design "compon independent", that is the lowest priced available components can be used in a system meeting designed system perform guarantees that RFID tag components can always be acquired on competitive bids at the lowest possible unit prices. Co independent design requires technical flexibility because of the large number of possible combinations of antenna materi substrates, chip impedances, etc. as well as effects of antenna loading by product packaging and other environmental ef show that this large number of possibilities can be treated by genetic algorithm based design techniques that optimize an geometries to particular RFID chip impedances and accommodate various materials properties of the antenna, substrate electromagnetic environment of the RFID tag. The combinatoric explosion of RFID design parameters is addressable by computation using commodity PCs, giving a cost-effective scalable implementation path. Analysis by electromagnetic sir

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